Weed Science, 49:543–548. 2001

A thermal application range for postemergence pyrithiobac applications

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Pyrithiobac control of Palmer amaranth on the Texas Southern High Plains was correlated previously with temperature at the time of application. In the present study, the thermal dependence of pyrithiobac efficacy was used to define a thermal application range (TAR) for postemergence pyrithiobac applications. Several years of temperature data from four cotton-growing regions of the United States were analyzed with respect to the TAR to determine the extent to which temperature limitations could affect pyrithiobac applications. Temperatures outside the TAR occurred in all years and regions analyzed. Analyses of four geographic regions utilizing 4 to 11 yr of data for each region indicated the following percentages of hours inside the TAR: Lubbock, TX, 54 to 94%; Maricopa, AZ, 27 to 33%; Raleigh-Durham, NC, 70 to 97%; and Jackson, MS, 81 to 99%. A detailed analysis of the frequency and duration of the TAR in Lubbock, TX, showed that, periodically, temperatures outside the TAR may limit the efficacy of postemergence pyrithiobac applications for several consecutive days. Finally, the TAR was shown to be useful as a postapplication diagnostic tool for evaluating herbicide applications that resulted in poor efficacy. These results suggest that long-term evaluation of historic temperatures with respect to the TAR for a given herbicide may provide insight into the potential limitations of herbicide efficacy and underscore the potential utility of developing TARs based on field and laboratory analyses of herbicide thermal dependence.

Nomenclature: Pyrithiobac; cotton, *Gossypium hirsutum* L.; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA.

Key words: Acetolactate synthase, computer visualization, probability-based analyses.

Pyrithiobac was the first postemergence (POST) topical herbicide registered for use in cotton that effectively controls Palmer amaranth and other annual broadleaf weeds without the risk of yield or fiber quality reductions that are observed with POST treatments of fluometuron or MSMA (Guthrie and York 1989; Shankle et al. 1996; Snipes and Byrd 1994). However, inconsistent weed control by pyrithiobac has been observed since its commercial introduction in 1996 (Hurst 1998; Smith et al. 1997). Inconsistency in POST weed control may be attributed to application, biotic, or abiotic factors, including temperature (Light 1999). Harrison et al. (1996) reported that pyrithiobac applications made at controlled air temperatures of 25 and 30 C reduced velvetleaf (*Abutilon theophrasti* Medic.) fresh weight more effectively than applications made at 35 C.

Temperature may affect herbicide uptake, translocation, and degradation; therefore, it has been a key parameter investigated as a source of variability for foliar applications of herbicides inhibiting acetolactate synthase (ALS; EC 4.1.3.18) (Gallaher et al. 1999; Olson et al. 1999). A novel source of temperature limitation on ALS efficacy was reported to be the thermal dependence of ALS inhibition at the site of action (Light et al. 1999). In that study, the thermal dependencies for the in vitro inhibition efficiency and field activity of pyrithiobac on Palmer amaranth were highly correlated ($r^2 = 0.88$). Based on field studies that resulted in at least 90% control 14 d after treatment, application temperatures of 20 to 34 C were recommended for Palmer amaranth control with pyrithiobac POST. However, the utility of this recommendation is dependent on the frequency of temperatures that fall within the recommended range. The concept of a thermal application range (TAR) derived from laboratory or field analyses provides a means of assessing temperature restrictions on herbicide applications. The objective of this research was to develop probability-based tools for the use of a TAR and to employ them in the analysis of thermal limitations on pyrithiobac applications. In this study, the Palmer amaranth/pyrithiobac TAR was used to analyze temperature data from four cotton-producing regions to determine (1) which regions are potentially subject to thermal limitations, (2) the characteristics of thermal limitations in regions where the potential for thermal limitations exist, and (3) the utility of a TAR as a postapplication diagnostic tool for evaluating herbicide applications that resulted in poor efficacy.

Materials and Methods

Three levels of analysis were performed in this study: regional, intraregional, and episodic. At the regional level, locations representing each of the four cotton-growing regions of the United States were chosen: Maricopa, AZ (West), Lubbock, TX (Southwest), Jackson, MS (South), and Raleigh-Durham, NC (Southeast). The intraregional analysis was more detailed and focused on the specific characteristics of the TAR applied to data from Lubbock, TX, a region that is subject to potential thermal limitations. The episodic analysis used the TAR to examine reported poor

Palmer amaranth control following pyrithiobac applications at Lubbock, TX, in 1993 and at Maricopa, AZ, in 1997.

Because a great deal of capital investment is associated with climate-related farm management decisions, whenever possible, these decisions should be based, in part, on a quantitative analysis of long-term climatic records (Meyer et al. 1996). Temperature data from Texas were compiled from as early as June 9 through July 16 from 1990 through 2000. Data from Arizona, Mississippi, and North Carolina were compiled from June 9 through July 16 in 1997 through 2000. The June 9 to July 16 time frame was established because it represented the most probable timing of POST pyrithiobac applications on the Texas Southern High Plains (J. W. Keeling, personal communication), the region where the TAR was originally developed. Air temperature in Lubbock, TX, was monitored with a standard type J thermocouple.[1] The temperature was observed every second, and averages were recorded every 15 min using a data logger.[2] Archived temperature data from Arizona (AZMET 2000) and Mississippi and North Carolina (NCDC 2000) were hourly observations.

The pyrithiobac TAR for Palmer amaranth (20 to 34 C) used in the analysis was derived on the basis of recommendations made by Light et al. (1999). The 8:00 A.M. to 8:00 P.M. time interval (hereinafter referred to as "daylight hours") was used because it represented the majority of daylight hours during a typical herbicide use season when applications would be made. The air temperature data were limited to temperatures between 20 to 34 C and times between 8:00 A.M. to 8:00 P.M. using the filter feature on Microsoft® Excel (Anonymous 1997) to determine the daily duration of the TAR for POST pyrithiobac applications.

Empirical analysis of climate data can be made by determining the probability, duration, and frequency of an environmental parameter (Sivakumar 1992). Probability was calculated by dividing the annual sum of hours within the range by the sum of total hours evaluated in each herbicide use season. Frequency of each duration was determined by the number of days in each year where the applicable interval was within a specified length of time.

Three-dimensional computer visualizations of the seasonal patterns of pyrithiobac application limitations were made on a Silicon Graphics® computer using Fledermaus® software (Anonymous 1996) by inputting comma-delimited data consisting of the day of year, time of day, and temperature. An overlaying color map that corresponded to temperatures below, within, and above the TAR was created by technicians at IVS, Inc.[3]

Results and Discussion

Regional Analysis

Temperature data from four cotton-producing regions were evaluated using the pyrithiobac TAR developed for Palmer amaranth on the Texas Southern High Plains. Table 1 shows the probability of occurrence of POST pyrithiobac TAR in Arizona, Texas, Mississippi, and North Carolina. The effect of restricting pyrithiobac applications only to times when the temperature is within the TAR was most significant in Arizona. In this region, the TAR did not occur during more than 33% of the daylight hours in any of the 4 yr evaluated. Additionally, entire days outside the TAR in Arizona were due to temperatures exceeding 34 C (data not shown). This can be contrasted with 4 yr of data from North Carolina and Mississippi, where the TAR occurred during at least 70% of the daylight hours in every year. Entire days outside the TAR in North Carolina were due to temperatures below 20 C (data not shown). Over the 11 yr evaluated in Texas, the occurrence of temperatures within the TAR varied from 54 to 94%. The only years where an entire day was outside the TAR were 1990 (day 194), 1991 (day 162), and 2000 (day 169), and these were temperatures below 20 C (data not shown).

TABLE 1. Probability of occurrence of postemergence pyrithiobac thermal application range (TAR)[a] in four U.S. cotton (*Gossypium hirsutum*)-producing regions.

Location	Year	Hours inside TAR	Days completely outside range	Julian calendar days analyzed[b]	Total days
		%			
Arizona	2000	29	0	160–197	38
	1999	27	2	160–197	38
	1998	33	3	160–197	38
	1997	30	0	160–197	38
Mississippi	2000	84	0	160–197	38
	1999	99	0	160–197	38
	1998	81	0	160–197	38
	1997	99	0	160–197	38
North Carolina	2000	97	0	160–197	38
	1999	70	4	160–197	38
	1998	95	0	160–197	38
	1997	91	0	160–197	38
Texas	2000	83	1	160–197	38
	1999	81	0	160–197	38
	1998	54	0	160–197	38
	1997	80	0	160–197	38
	1996	62	0	166–197	32
	1995	70	0	174–197	24
	1994	79	0	160–197	38
	1993	94	0	160–197	38
	1992	82	0	160–197	38
	1991	92	1	160–197	38
	1990	63	1	160–197	38

[a] TAR is 20 to 34 C and was evaluated between 8:00 A.M. and 8:00 P.M.
[b] Dates were analyzed from June 9 (or the first date available on data provided by technicians at USDA-ARS in Lubbock, TX) to July 16 in each year.

Based on 4- or 11-yr averages, it was predicted that the TAR would occur during 30% of the daylight hours in Arizona, 75% of the daylight hours in Texas, and 90% of the daylight hours in both Mississippi and North Carolina. Therefore, applications could be made essentially without regard to temperature across the 2.9 million ha of cotton in the South and Southeast. However, it is likely temperature would limit pyrithiobac applications made across the 450,000 ha of cotton in the West if applications were made only when temperatures were within the TAR. In the Southwest, adherence to the TAR would likely improve POST pyrithiobac efficacy following any application made to the 2 million ha of cotton growing in this region. It has been shown that applications made when temperatures are outside the TAR have resulted in continued growth of Palmer amaranth that was as much as 72% of the nontreated control (Light et al. 1999).

Table 2. Frequency and duration of postemergence pyrithiobac thermal application range (TAR)[a] on the Texas Southern High Plains from June 9 to July 16.

Year	Hours ≤ 2	> 2 and ≤ 4	> 4 and ≤ 6	> 6 and ≤ 8	> 8	Total
	Days					
2000	2	0	3	3	30	38
1999	0	1	2	6	29	38
1998	0	7	19	3	9	38
1997	0	0	7	5	26	38
1996	1	13	6	2	10	32
1995	0	4	5	5	10	24
1994	0	3	4	8	23	38
1993	0	0	0	3	35	38
1992	0	1	3	6	28	38
1991	2	0	0	3	33	38
1990	1	7	12	6	12	38

[a] TAR is 20 to 34 C.

Table 3. Frequency and duration of temperatures (T) < 20 C on the Texas Southern High Plains from June 9 to July 16.

Year	Hours ≤ 2	> 2 and ≤ 4	> 4 and ≤ 6	> 6	Total (T < 20 C)	Total
	Days					
2000	11	3	1	2	17	38
1999	8	8	2	1	19	38
1998	6	1	0	0	7	38
1997	13	8	1	2	24	38
1996	3	1	0	0	4	32
1995	6	2	0	0	8	24
1994	10	1	0	0	11	38
1993	12	2	0	0	14	38
1992	12	5	1	0	18	38
1991	16	2	1	1	20	38
1990	9	1	0	1	11	38

Intraregional Analysis

Although occurrence of temperatures outside the TAR suggests that pyrithiobac efficacy could be negatively affected, the analysis of the frequency and duration of those periods allows for further evaluation of how adherence to the TAR may constrain pyrithiobac applications. Constraints on herbicide application are particularly important in light of the need to apply the herbicide to plants of small size to achieve good control. Table 2 shows the frequency and duration of the pyrithiobac TAR on the Texas Southern High Plains. The TAR lasted for a period exceeding 8 h on 12, 10, 10, and 9 of the 38 d evaluated in 1990, 1995, 1996, and 1998, respectively. However, in 1991, 1993, and 2000, the TAR lasted for a period exceeding 8 h on 33, 35, and 30 of the 38 d evaluated, respectively. Thus, in 1991, 1993, and 2000, pyrithiobac applications could have been made virtually without regard to temperature limitations. However, the low occurrence of temperatures inside the TAR in 1990, 1995, 1996, and 1998 implies that pyrithiobac applications would have been restricted during approximately three-fourths of the growing season in these years to avoid the risk of making applications that resulted in poor weed control. On average during the 11-yr evaluation, temperatures inside the TAR occurred for more than 8 h on 22 of the 38 d evaluated (58%). Temperatures fell outside the TAR for periods of ≤ 2 h after the TAR had been achieved on less than 3 d in each year (data not shown); therefore, the effect of being outside the TAR for a short period of time following a pyrithiobac application would be negligible.

Table 3 shows the frequency and duration of temperatures below 20 C on the Texas Southern High Plains. In 1991, there was a total of 20 d when the temperature was below 20 C, but 80% of the time the low temperatures lasted for less than 2 h. On 4 d in 1996 the temperature was below 20 C, and on three of those days the duration of the cool period was less than 2 h. On average, there were 10 d when the temperature was below 20 C for less than 2 h. Although no field studies have examined pyrithiobac efficacy at temperatures below 20 C, it is possible that the occurrence of these brief periods of low temperatures could affect pyrithiobac efficacy because of decreased inhibition efficiency at the site of action. Decreased inhibition efficiency at temperatures below 20 C has been shown in previous in vitro studies of Palmer amaranth ALS (Light et al. 1999). Additionally, the potential for moderate to severe cotton injury from pyrithiobac appears to be greater when the herbicide is applied during or shortly before a period of cool temperatures (York and Culpepper 2000). However, because these cooler temperatures predominantly occur in the early hours of the morning, applications could be delayed until the temperature is within the TAR to achieve acceptable Palmer amaranth control and reduce the risk of cotton injury.

Figure 1 shows the distribution of days with temperatures below 20 C for periods of 4 h or more. Because of the time required to mix herbicide solutions, calibrate spray equipment, and travel to the application site, interruptions in the TAR of less than 4 h are considered to have little effect on the ability to make pyrithiobac applications, whereas interruptions of greater than 4 h may impede herbicide applications. In 1991 and 1997, there were two times when the temperature was below 20 C for 4 h or more, and this occurred on two consecutive days. However, in many years (1993 to 1996 and 1998), there were no occurrences when

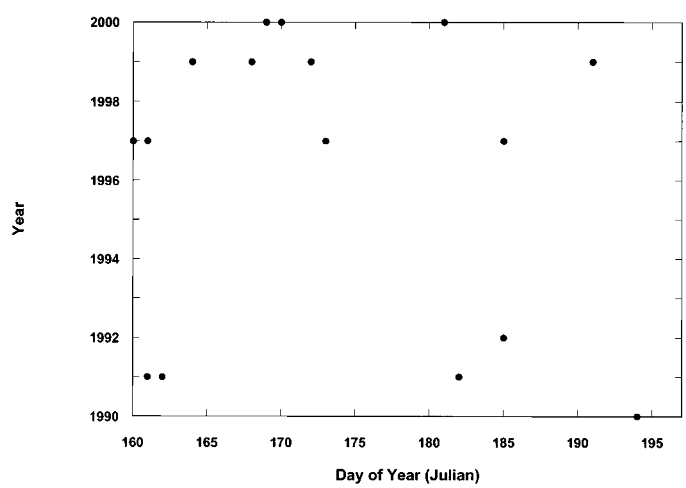

Figure 1. Distribution of days when the temperature was below 20 C for ≥ 4 h on the Texas Southern High Plains.

Table 4. Frequency and duration of temperatures (T) > 34 C occurring on the Texas Southern High Plains from June 9 to July 16.

Year	Hours				Total (T > 34 C)	Total
	≤ 2	> 2 and ≤ 4	> 4 and ≤ 6	> 6		
	Days					
2000	1	2	0	3	6	38
1999	1	2	2	2	7	38
1998	3	0	11	18	32	38
1997	0	2	4	2	8	38
1996	2	5	2	14	23	32
1995	2	3	3	6	14	24
1994	2	3	5	6	16	38
1993	0	3	0	0	3	38
1992	0	2	4	3	9	38
1991	0	0	0	0	0	38
1990	3	2	6	14	25	38

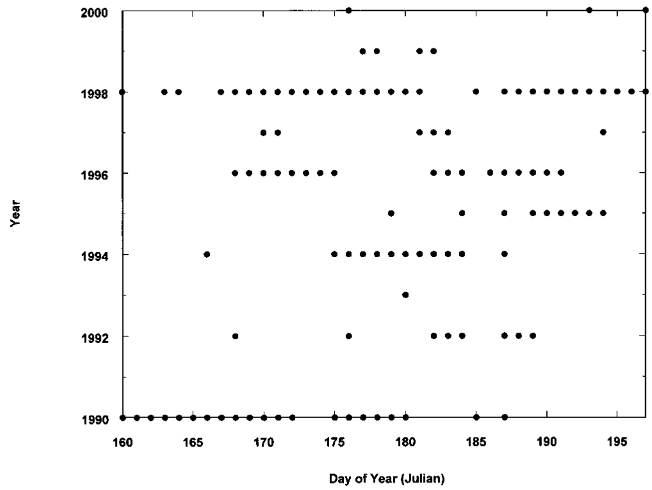

Figure 2. Distribution of days when the temperature exceeded 34 C for ≥ 4 h on the Texas Southern High Plains.

the temperature was below 20 C for a period of more than 4 h. These data show that extended periods with temperatures below 20 C are relatively uncommon and will have little effect on pyrithiobac applications in the Southwest.

The frequency and duration of temperatures exceeding 34 C on the Texas Southern High Plains are shown in Table 4. In 1998, there were a total of 32 d where the temperature exceeded 34 C. On 18 of those 32 d, the duration was for a period greater than 6 h. In 1991, there were no days when the temperature exceeded 34 C. On average, there were 7 d when the temperature exceeded 34 C for more than 6 h. These long periods of temperatures exceeding 34 C may be significant because greater than 6-h durations mean that more than half of the daylight hours are outside the recommended application range. This would provide a narrow window for applications, which may be impractical where a large number of acres are infested with weeds. It is unlikely that increasing the pyrithiobac rate would improve weed control at temperatures exceeding 34 C. Pyrithiobac applied at 105 g ai ha^{-1} (1.5 times the labeled rate) to Palmer amaranth did not result in acceptable control when temperatures were above 34 C (Light et al. 1999). In West Texas, where continuous cotton is grown, this is the maximum amount of product that can be applied in a year (Anonymous 2000).

Potential limitations of high temperature can be determined by considering the number of consecutive days with temperatures greater than 34 C for periods ≥ 4 h (Figure 2). There were two times in 1990 and 1996 when there were at least 6 consecutive days with temperatures exceeding 34 C for greater than 4 h. In 1998, there were two times when there were 11 or more consecutive days with temperatures exceeding 34 C. There was only 1 d in 1993 when temperatures exceeded 34 C for more than 4 h, and there were no days in 1991 when the temperature exceeded 34 C for 4 h or more. Preparation for and completion of herbicide application require several hours; therefore, extended periods of time where temperatures exceed 34 C may prevent pyrithiobac applications for a number of consecutive days. Palmer amaranth has been shown to grow an average of 19.7 cm wk^{-1} (Keeley et al. 1987) or 0.2 cm per growing degree day (Horak and Loughin 2000). Therefore, it is possible that Palmer amaranth may grow beyond the height of 0.6 to 10 cm recommended to achieve optimum pyrithiobac efficacy (Anonymous 2000) in as little as 4 d. Postemergence pyrithiobac applications made to weeds beyond the proper growth stage have resulted in less than acceptable weed control (Jordan et al. 1993). Potential loss of weed control should be considered in light of reported lint reductions of 5.2 to 9.3% for each increase of 1 kg of Palmer amaranth biomass (Rowland et al. 1999).

Computer visualization of climatic data has been shown to improve communication in pest management planning processes (Lynch et al. 1994). To visually interpret the significance of seasonal patterns of pyrithiobac application limitations on the Texas Southern High Plains, three-dimensional computer images were created. Figure 3 (top) shows images visualizing the application limitations in 1993 when 94% of the daylight hours were within the TAR. Green is the dominant color and represents times favorable for pyrithiobac POST treatments. Blue and red regions represent times when temperatures were below and above the TAR, respectively, and would not be favorable times for pyrithiobac POST treatments. In 1994, 79% of the daylight hours were within the TAR (Figure 3, middle) and would most closely represent the average of 76%. A visualization of application limitations for 1998 is shown in Figure 3 (bottom). In 1998, only 54% of the daylight hours were within the TAR; therefore, red is more predominant compared to the figure for application limitations in 1993. These visualizations may allow applicators to perceive the probability of risk associated with making pyrithiobac treatments outside the TAR. This type of spatial analysis has been used to visually interpret crop growth, development, and yield (Engel et al. 1997; Thorton et al. 1997); trends and fluctuations in annual precipitation (Garbrecht and Fernandez 1994); results of timber harvests (McGaughey 1998); nonpoint source pollution (Srinivasan and Engel 1994); and groundwater vulnerability to pesticide contamination (Soutter and Pannatier 1996).

Episodic Analysis

The TAR can be used as a diagnostic tool to assess the role of temperature limitations on herbicide efficacy when

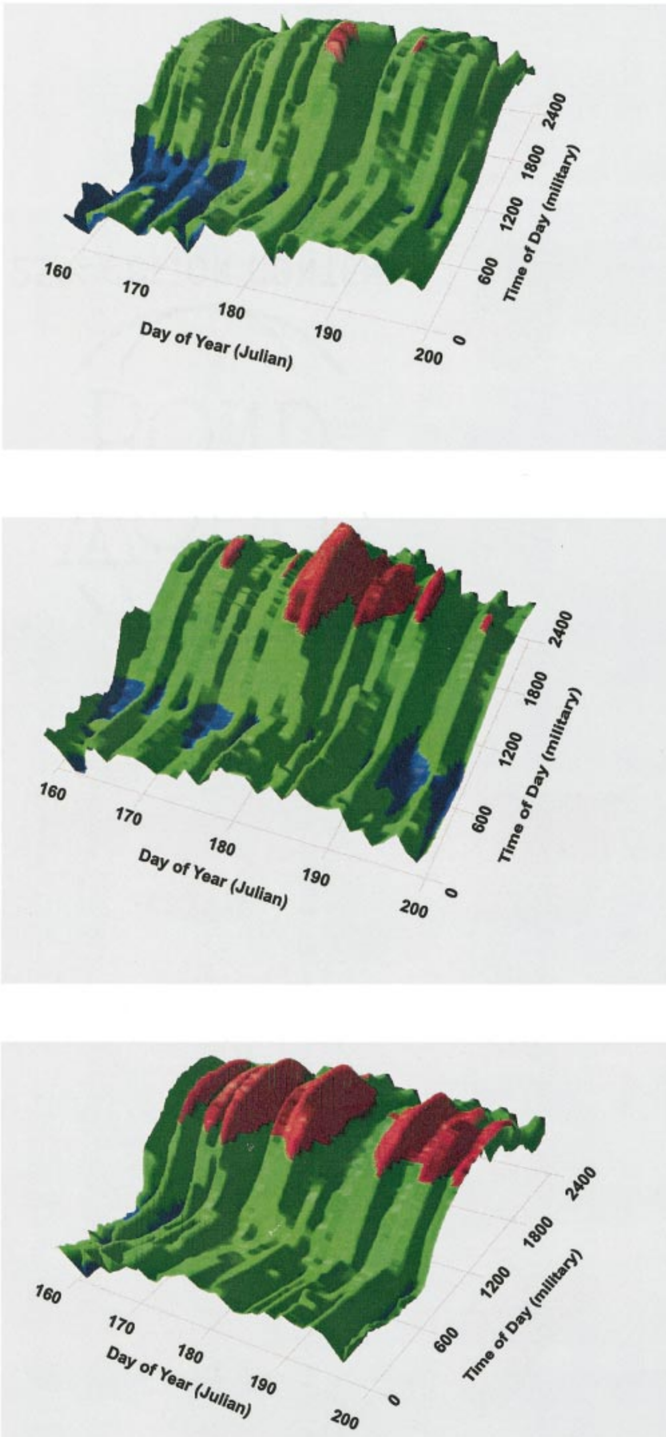

FIGURE 3. Computer visualizations of seasonal patterns of postemergence pyrithiobac application limitations in 1993 (top), 1994 (middle), and 1996 (bottom) on the Texas Southern High Plains. The *x*-axis represents day of year (Julian), the *y*-axis represents time of day (military), and the height represents air temperature (C). The color overlay maps temperatures within and outside of the postemergence pyrithiobac thermal application range. Red represents temperatures exceeding 34 C, blue represents temperatures below 20 C, and green represents temperatures between 20 and 34 C.

poor weed control following a POST pyrithiobac treatment has been reported. If the temperature at the time of application was within the TAR, then the possibility that temperature affected efficacy is reduced. However, if the temperature at the time of application was outside the TAR, then temperature limitations could be a contributing factor to reduced efficacy. For example, Dotray et al. (1996) observed 100, 97, and 83% Palmer amaranth control 6 wk after treatment following pyrithiobac POST at 140 g ha^{-1} in 1991, 1992, and 1993, respectively. The reduced efficacy in 1993 resulted from an application made on June 9. Examination of the TAR for June 9 (day 160) in 1993 showed that 11 of 12 h were within range. This evidence suggests that temperature limitations did not contribute significantly to the reduced efficacy. With the elimination of temperature as a significant factor, other environmental factors could be examined. Archived precipitation data (NNDC 2000) for 1993 showed that from January 1 to June 9, only 12.7 cm of rain had been received at Lubbock, TX. Additionally, in the 21 d prior to June 9, only 0.4 cm of rain had fallen at Lubbock. Therefore, it is possible that dry soil conditions at the time of pyrithiobac application could be a causal factor in the reduction of Palmer amaranth control.

A second example of using the TAR as a diagnostic tool is examination of a study conducted at the Maricopa Agricultural Center in Arizona. McCloskey (1998) reported 66% Palmer amaranth control 19 d after treatment following pyrithiobac POST at 105 g ai ha^{-1} on May 28, 1997. Examination of the TAR for May 28 (day 148) showed that the temperatures were inside the TAR for only 3 of 12 h. In this case, the evidence suggests that temperature at the time of application could have been a causal factor in the poor pyrithiobac efficacy.

The term TAR was used in this study to describe a range of temperatures that are conducive to acceptable weed control. The practical use of a TAR to optimize herbicide efficacy was investigated in this study by developing tools for assessing the significance of the TAR for a defined herbicide and target species. The tools can be used to evaluate the potential role of temperature on herbicide efficacy at three levels: regional, intraregional, and episodic. At the regional level, the analysis of long-term climate data can be used to broadly define thermal limitations. In some areas, it may be possible to eliminate temperature limitations on herbicide efficacy, whereas in other areas, the analysis may underscore the limitations. Analyses of the frequency and duration of a defined TAR in a specific region can provide information on the extent of an herbicide's thermal limitations. In some years, there may be difficulty finding sufficient time when temperatures are within the TAR to control target species effectively. Alternatively, the analysis might indicate that, provided all else is equal, weed control could be improved by making applications when temperatures are within the TAR. Finally, TARs may be used to evaluate episodes of diminished efficacy to help determine whether or not weed control differences can be ascribed to temperature.

Sources of Materials

[1] Type J duplex wire thermocouple, Newport Electronics, Inc., 2229 S. Yale Street, Santa Ana, CA 92704.

[2] Datalogger, model 21X, Campbell Scientific, P.O. Box 551, Logan, UT 84321.

[3] Overlaying color map, IVS, Inc., Fredericton, New Brunswick, Canada.

Acknowledgments

Contribution of the Department of Plant and Soil Science, College of Agricultural Sciences and Natural Resources, Texas Tech University, publication T-4-479. This work was supported in part by funding from the Institute for Research in Plant Stress, College of Agricultural Sciences and Natural Resources, Texas Tech University.

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Received December 12, 2000, and approved February 22, 2001.